A Heterodyne Receiver at 533 GHz using a Diffusion-Cooled Superconducting Hot Electron Bolometer Mixer

A. Skalare, W. R. McGrath, B. Bumble and H. G. LeDuc
Center for Space Microelectronics Technology, Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, CA 91109

P. J. Burke, A. A. Verheijen and D. E. Prober
Dept. of Applied Physics, Yale University, New Haven, CT 06520-8284

Abstract— This paper describes heterodyne measurements at 533 GHz using a novel superconducting hot electron bolometer in a waveguide mixer block. The bolometer is a thin (10 nm) and narrow (0.1 μm) strip of niobium with a length of less than half a micron and a critical temperature of approximately 5.5 K. The short length ensures that diffusion dominates over electron-phonon interaction as a cooling mechanism for the hot electrons, thus allowing heterodyne detection with intermediate frequencies of several GHz. A Y-factor response of 1.15 dB has been obtained at an intermediate frequency of 1.4 GHz with hot/cold load temperatures of approximately 295/77 K, indicating a receiver noise temperature around 650 K DSB. The IF response extends up to at least 2 GHz and possibly higher.

I. INTRODUCTION

Due to its high sensitivity, the niobium SIS quasiparticle mixer is the heterodyne detector of choice for astronomical observations in most of the millimeter and submillimeter wave bands. Unfortunately the sensitivity deteriorates rapidly at frequencies higher than the superconducting gap frequency, which is 700-750 GHz for good niobium films. SIS junctions based on other materials such as NbN, which has a gap frequency near 1400 GHz may eventually operate well at higher frequencies, but this has not yet been shown.

An alternative to SIS tunnel junctions at frequencies above 1 THz are mixers based on superconducting hot electron transition-edge bolometers. These devices rely only on electron heating, and the mixing response is not limited by the superconducting gap frequency. Due to the finite time required to cool the heated electrons, however, there is an upper limit to the intermediate frequency (IF). This is an important issue, since an IF of several GHz is required for many practical applications.

Superconducting bolometer mixers that rely on electron-phonon interactions to cool the hot electrons have been proposed and recently studied experimentally at microwave and millimeter wave frequencies [1-4]. Thermal relaxation times of ~1-2 ns for Nb bolometers have been obtained in agreement with expected values. The measured IF 3 dB roll-off frequency is around 100 MHz. NbN films have shown IF roll-offs near 1 GHz [5]. While these bolometer mixers perform reasonably well, the thermal response time is too slow to allow for useful intermediate frequencies.

Manuscript received October 17, 1994.
The research described in this paper was performed by the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology and by Yale University and was jointly sponsored by the BMDO Innovative Science and Technology Office, the National Science Foundation, the Netherlands Organization for Scientific Research and the National Aeronautics and Space Administration, Office of Space Access and Technology. Funding for P. J. Burke was provided by a NASA Graduate Student Fellowship as well as a Connecticut High Technology Fellowship.

A different type of superconducting hot electron bolometer that uses a diffusion cooling mechanism was recently proposed [6]. The bolometer is a short (< 0.5 μm) and narrow (~0.1 μm) niobium microbridge that is contacted by large normal-metal (Au) films. The short bridge length ensures that the thermal conductance associated with out-diffusion of the hot electrons into the gold will dominate over that of the electron-phonon interactions by more than a factor of 10. IF roll-off frequencies of 4 GHz are expected for a total microbridge normal resistance of 80 Ω and a length of 0.2 μm. The microbridge is thin (~10 nm), which ensures a short mean free path (~1-10 nm) resulting in an enhanced electron-electron interaction. This ensures that the dissipated energy is shared by the electrons within the bridge and allows the electron temperature to increase relative to the lattice when absorbing RF power. The device resistance R is a function of the electron temperature T. The nonlinear R versus T characteristic at the superconducting transition provides the mechanism for heterodyne mixing.

This paper describes the first heterodyne measurements with a diffusion-cooled bolometer mixer. This device yields low-noise and wide IF bandwidth with a local oscillator frequency of 533 GHz. The results agree well with the expected performance and hence demonstrate the usefulness of this new device.

II. DEVICE GEOMETRY AND FABRICATION

The bolometer consists of a 0.14 μm wide strip of niobium. The length L of the device is determined during fabrication by the gap between the contacting gold pads; see Fig. 1. L is 0.27 μm for the device used in the receiver measurements. The thick niobium leads form the waveguide probe and RF filter that can be seen in Fig. 2. The bolometer was fabricated on a 100 μm fused quartz substrate, that was later lapped down to 50 μm and diced.

The first step in the fabrication is a lift-off process with deposition of 110 nm of magnetron sputtered Nb and 30 nm of evaporated gold for the base wiring layer (the niobium leads in Fig. 1). Next, a blanket deposition of 10 nm of Nb and 10 nm of Au is made. (A low resistance contact between the gold and Nb is important for the speed of the bolometer. Excess contact resistance could decrease the thermal conductance.) A 30 nm chromium etching mask defining the bolometer is patterned using electron beam lithography with

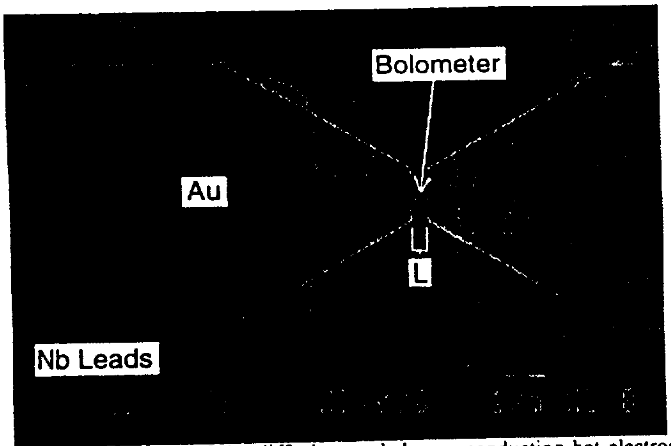

Fig. 1. SEM image of the diffusion cooled superconducting hot electron bolometer.

PMMA liftoff. The bolometer is patterned by argon sputtering the thin gold layer, and by reactive ion etching of the niobium with a mixture of CCl_2F_2+CF_4+O_2. The chromium etching mask is removed by a wet etch. The normal metal pads were formed by thermal deposition of 100 nm of gold, using e-beam lithography and PMMA in a lift-off process. The remaining patch of 10 nm of gold directly on top of the microbridge was then removed by an argon sputter etch. The devices were passivated by 40 nm of SiO.

III. EXPERIMENTAL RECEIVER SET-UP

The heterodyne measurements were carried out in a modified waveguide receiver [7]. The quartz substrate with the bolometer was installed in a two-tuner waveguide mixer block with cyanoacrylate glue; Fig. 2 shows the mixer block. DC and IF connections were made with aluminum wires that were ultrasonically bonded to both ends of the device. The mixer block and focusing mirror were mounted to the LHe cold plate in a commercial vacuum cryostat as shown in Fig. 3. The cryostat employs a 77 K heat shield, as well as a heat shield connected to the LHe cold plate. Fluorogold™ infrared filters on each shield reduce the room temperature heat flux into the cryostat. An additional third heat shield was built around the mixer block itself, and this was heat sunk to the LHe cold plate, as shown in Fig. 3.

The local oscillator (LO) source was a ×2×3 frequency multiplier that was pumped by a Gunn oscillator operating at ~90 GHz. The LO power was coupled into the cryostat window as shown in Fig. 3. For the Y-factor measurements, a folded Fabry-Perot interferometer was used to separate the LO and signal beam paths. For measurements with a monochromatic source, the Fabry-Perot was replaced by a simple aluminum mirror. The monochromatic source was provided by a signal from a second Gunn oscillator, that was coupled into the multiplier through a -20 dB waveguide coupler [8]. As a result, the multiplier generated a strong local oscillator line at 533 GHz, and a weak "signal" line separated from the local oscillator line by the difference between the two Gunn frequencies. The local oscillator power and the signal were both coupled into the cryostat by the

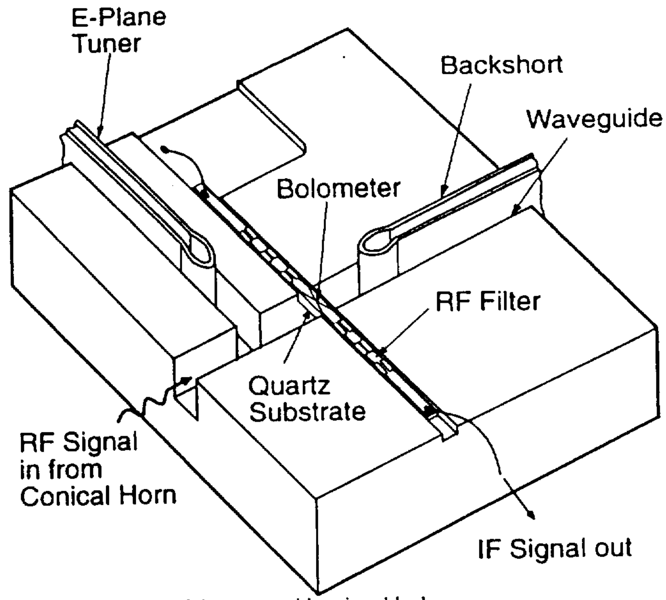

Fig. 2. Split view of the waveguide mixer block.

aluminum mirror. This approach was chosen since only one suitable multiplier was available for the experiment.

The intermediate frequency (IF) amplifier configuration was designed for operation around 1.4 GHz. The output port on the mixer block was connected to an isolator and a low-noise cooled HEMT amplifier placed inside the cryostat. This circuitry provided close to 50 Ω input impedance over the entire IF band. Room temperature amplifiers provided additional gain. The IF output was measured with a power meter and, through a 10 dB directional coupler, with a spectrum analyzer. The total IF system gain was about 94 dB and the system noise temperature was 6 K. The bandwidth for receiver noise measurements was 324 MHz as set by a bandpass filter. For measurements with the monochromatic

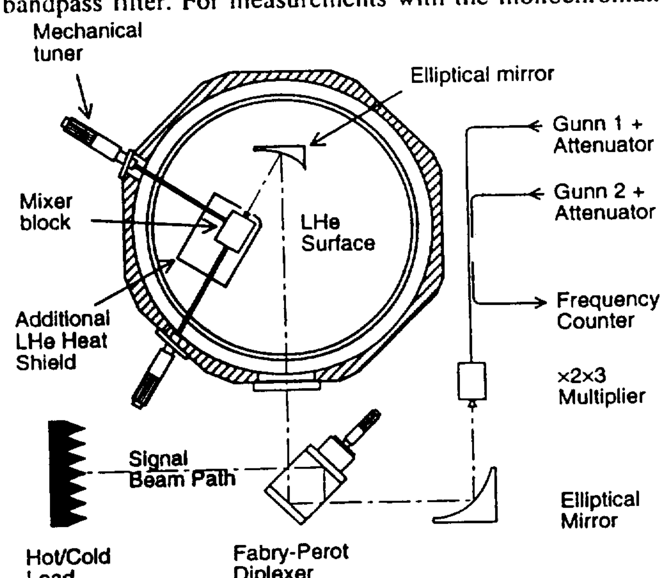

Fig. 3. Schematic view of the cryostat used in the receiver measurements. The reference plane for the noise measurements is the position of the hot/cold load. For the measurements with a monochromatic source, the Fabry-Perot diplexer was replaced by a simple mirror.

source, the bandpass filter was removed to allow intermediate frequencies up to 2 GHz.

IV. Receiver Measurements

A. Y-Factor Measurements

Y-factor measurements were performed with hot (295K) and cold (77K) loads in the receiver signal path. The LHe bath temperature was reduced by pumping on the helium tank. This resulted in a temperature of 2.19 K for the waveguide mixer block. The waveguide backshort and E-plane tuner were optimized for maximum LO coupling at 533 GHz. IV-curves were measured for several levels of LO pump power, together with the output power of the IF amplifier system. Fig. 4 shows the data for the optimum LO pump level. The best response is found in the resistive branch of the IV-curve just above the bias point where the device switches back into the low-resistance state. The largest Y-factor is 1.15 dB, indicating a double sideband (DSB) receiver noise temperature of just under 650 K. This is close to the theoretically expected noise [6] given our transition temperature 5.5 K, transition width of ≈ 0.5 K, IF system noise of 6 K, and experimentally estimated mixer conversion efficiency (discussed below). Lower noise temperature is possible for lower T_C and broader transition widths [6].

In a separate measurement the noise temperature and gain of the IF system were accurately determined by connecting the input port to a temperature controlled 50 Ω termination in place of the mixer block. Using this calibration, it is possible to estimate the conversion efficiency η and noise temperature T_m of the bolometer mixer (note that these mixer parameters still include contributions from the warm and cold optics as well as diplexer losses). This gives $\eta \approx -11.4$ dB (DSB) and $T_m \approx 560$ K (DSB). The conversion efficiency is about 3-4 dB lower than expected theoretically [6].

An important issue for a bolometer mixer is the response due to the broadband power from the hot load used during receiver noise measurements. For broadband RF coupling, this thermal source could warm the lattice as well as saturate the mixer. To ensure that we were correctly measuring the intrinsic heterodyne properties, this effect was monitored by observing the DC bias voltage change at the best mixing point caused by the RF hot and cold loads. The change was typically less than 2 μV. From experimentally measured changes in the IV curve with temperature and the measured thermal conductance [8] of the bolometer, it was possible to estimate that the hot load power was significantly less than the LO power level. In addition, if excessive heating were present, the IF power curves shown in Fig. 4 would separate for bias voltages above about 1 mV indicating that the bolometer was warming up and emitting more IF power. As can be seen, these curves converge, where there is no mixing response.

The receiver response was also measured at 4.3 K. Optimizing the backshort, E-plane tuner, and LO power yielded a Y-factor of 0.3 dB which corresponds to a receiver noise temperature of about 3000 K (DSB). The estimated mixer conversion efficiency was -19 dB (DSB). The increase

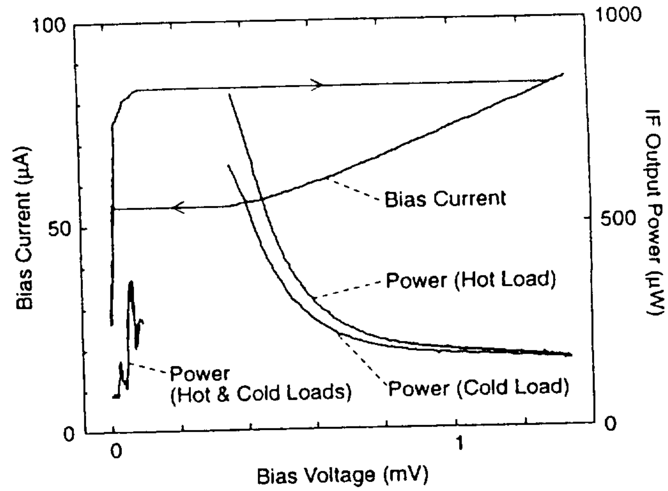

Fig. 4. The current-voltage (IV) curve for the bolometer with local oscillator power applied. The arrows show the regions in which switching occurs. The device resistance is negative below about 0.4 mV. The IF output power is shown for both a hot (295 K) and a cold (77 K) load in the receiver signal path.

in noise is likely due to the poorer conversion efficiency, and not to an increase in mixer noise since this is determined by the electron temperature which is always near Tc. Our explanation is supported by the fact that the increase in noise correlates well with the decrease in conversion efficiency.

B. Measurements with a Monochromatic Source

The IF output power was measured as a function of bias voltage both with and without an applied monochromatic signal; see Fig. 5. The local oscillator frequency was 533 GHz and the intermediate frequency was 1.4 GHz with the signal in the upper sideband. The same IF amplifier chain was used as in the Y-factor measurements, but the Fabry-Perot was replaced by an aluminum mirror. The temperature of the mixer block was 2.19 K. As seen in fig. 5, the IF response for the monochromatic rf signal has approximately the same dependence on bias voltage as the difference between the two power curves in the Y-factor measurement in Fig. 4. In fact, plotting the difference between the two power curves in fig. 5 versus the difference between hot and cold IF power curves yields a straight line if the same amount of local oscillator power is applied in the two measurements. This result is consistent with a heterodyne process.

The intermediate frequency dependency of the mixer output was studied by using the second Gunn oscillator in Fig. 3 as a signal source, and measuring the magnitude of the resulting line in the IF band with a spectrum analyzer. The frequency of the signal Gunn was tuned so that the IF varied from 1043 MHz to 1967 MHz. The Gunn used to generate the LO power was operated at a constant frequency of 88.03 GHz giving a local oscillator frequency of 528.18 GHz. The data were corrected for the gain variations of the IF amplifier chain at each measurement frequency. The temperature of the mixer block was 4.3 K in this experiment. As shown in Fig. 6 there is no indication of a high frequency roll-off up to 1.9 GHz. As discussed below, this is consistent with DC estimates of the thermal conductance of the microbridge

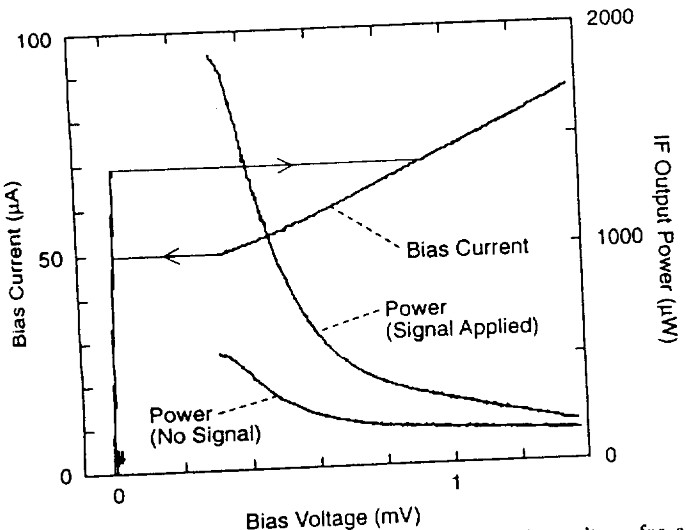

Fig. 5. The IF output power as a function of DC bias voltage for a monochromatic rf signal applied to the mixer. Also shown is the IV curve of the LO-pumped device. The arrows indicate the regions where switching occurs.

which indicate that the IF roll-off should be near 3 GHz. There are variations within the measurement band, however, that are most likely due to standing waves in the RF beam path as well as signal power variations from the multiplier at 530 GHz. Additional measurements were also made of the IF response from 2-4 GHz with broadband room temperature amplifiers, but again large variations in the rf signal path made determination of the roll-off frequency difficult. Thus further measurements are required to fully characterize the IF roll-off of this mixer.

From the experimental R versus T characteristics of a 0.2 μm long microbridge, the thermal conductance has been calculated to be approximately $G = 18$ nW/K [8]. With an estimated heat capacity $C = 10^{-18}$ J/K, this gives a thermal response time $\tau \approx C/G \approx 55$ ps. The intermediate frequency roll-off would then be $f = (2\pi\tau)^{-1} = 2.9$ GHz.

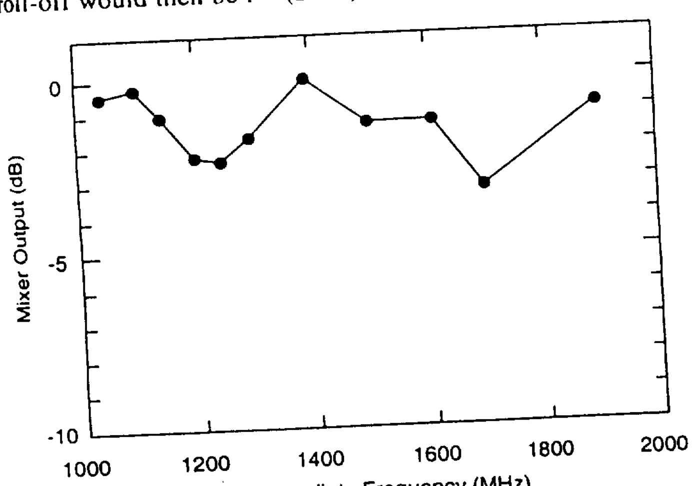

Fig. 6. The heterodyne output power of the bolometer as a function of intermediate frequency.

Summary

A novel type of transition-edge bolometer mixer that uses diffusion as a cooling mechanism for hot electrons has been demonstrated at 533 GHz. This mixer provides very low heterodyne receiver noise temperatures, 650 K (DSB), with high intermediate frequencies, 1.4 GHz. The IF response extends to at least 2 GHz. This is a significant improvement over competitive electron-phonon cooled bolometer mixers which are limited to much lower intermediate frequencies. The diffusion-cooled bolometer mixer is expected to work up to several tens of THz with little change in performance. It is thus a viable alternative to less-sensitive semiconductor mixers at very high (> 1 THz) submillimeter wave frequencies [9].

Acknowledgment

We thank Paul D. Maker and Richard E. Muller for their help with setting up the electron beam lithography facility at Jet Propulsion Laboratory.

References

[1] E. M. Gershenzon, G. N. Goltsman, I. G. Gogidze, Y. P. Gusev, A. I. Elantev, B. S. Karasik, A. D. Semenov, "Millimeter and Submillimeter Range Mixer Based on Electronic Heating of Superconducting Films in the Resistive State," Superconductivity 3 (10), pp.1582-1597 (1990).

[2] E. M. Gershenzon, G. N. Goltsman, B. S. Karasik, G. Ya. Lugova, N. A. Sebryakova, E. V. Chinkova, "IR Radiation Detectors Based on Electronic Heating of Films made from Conventional Superconductors in the Resistive State," Superconductivity 5 (6), p. 1126, (1992).

[3] H. Ekström, B. Karasik, E. Kollberg, K. S. Yngvesson, "Investigation of a Superconducting Hot Electron Mixer," Proc. 5th Int'l Symposium on Space Terahertz Technology, p. 169, May 10-12, 1994, Univ. of Michigan, Ann Arbor, Michigan.

[4] A. I. Elantev, B. S. Karasik, "Noise Temperature of a Superconducting Hot-Electron Mixer," Proc. 5th Int'l Symposium on Space Terahertz Technology, p. 225, May 10-12, 1994, Univ. of Michigan, Ann Arbor, Michigan.

[5] O. Okunev, A. Dzardanov, H. Ekström, S. Jacobsson, E. Kollberg, G. Goltsman, E. Gershenzon, "NbN Hot Electron Waveguide Mixer for 100 GHz Operation," Proc. 5th Int'l Symposium on Space Terahertz Technology, p. 214, May 10-12, 1994, Univ. of Michigan, Ann Arbor, Michigan.

[6] D. E. Prober, "Superconducting Terahertz Mixer using a Transition-Edge Microbolometer", Appl. Phys. Lett. 62 (17), pp. 2119-2121, (1993).

[7] P. Febvre, W. R. McGrath, P. Batelaan, B. Bumble, H. G. LeDuc, S. George, P. Feautrier, "A Low-Noise SIS Receiver Measured from 480 GHz to 650 GHz using Nb Junctions with Integrated RF Tuning Circuits", Int. J. Infrared & Millimeter Waves, Vol. 15, No. 6, pp. 943-965, (1994).

[8] A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, "A Superconducting Hot Electron Bolometer Mixer For 530 GHz", Proc. 5th Int'l Symposium on Space Terahertz Technology, p. 157, May 10-12, 1994, Univ. of Michigan, Ann Arbor, Michigan.

[9] R. Blundell and C.-Y. E. Tong, Proc. IEEE **80**, p. 1702 (1992).